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ADP023827

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TITLE: Proceedings of the HPCMP Users Group Conference 2004. DoD High Performance Computing Modernization Program [HPCMP] held in Williamsburg, Virginia on 7-11 June 2004

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Potential Discrepancies in Radar Signature Predictions for Ground Vehicles

William Coburn, Calvin Le, and William Spurgeon
US Army Research Laboratory (ARL), Aberdeen Proving Ground, MD
{wcoburn, cle, wspurge}@arl.army.mil

Abstract

An investigation of modeling issues at K_a-Band and above was conducted using Xpatch, a high-frequency radar signature prediction code based on the shooting and bouncing ray technique. The lessons learned apply to a large class of ground targets of interest for millimeter wave radar applications. We summarize the unclassified modeling results and computational requirements at K_a-band frequencies. The ground vehicle simulations indicate that accurate target representations are required to a resolution on the order of the wavelength. In many cases the available data corresponds to near-field measurements. In this case we use the Xpatch near-field simulations to better reproduce the measured radar signatures.

1. Introduction

The development of survivable Army platforms that are integral assets to the Army Vision—Future Combat Systems (FCS) requires advanced predictive design and prototyping that relies heavily on modeling and simulation to assess feasibility, optimize performance, and trade off competing requirements. The rapid acquisition cycle dictated by the Army Transformation to FCS makes radar signature simulations attractive for the design of next-generation military vehicles. For the Army to use radar signature predictions with confidence, the accuracy and limitations of high-frequency approximations must be well understood. In particular, the realistic simulation of radar measurements can be an important aspect of high-frequency signature comparisons. To examine some of these critical issues, we consider two tracked vehicles at K_a-Band frequencies, the ZSU-23-4 and T72M1. Xpatch simulations were designed to reproduce the test vehicle configurations and investigate discrepancies in comparison to monostatic radar cross section (RCS) data. We use flat, triangular facets to describe the target geometry to Xpatch which uses ray tracing and Physical Optics (PO) to calculate the scattered field[1,2]. We also investigate the RCS of a canonical tank scale-model (referred to as the T5M3 Mark 1) compared to compact range measurements[3]. The Xpatch study was conducted on the high performance computational (HPC) facilities at the US Army Research Laboratory (ARL) Major Shared Resource Center (MSRC) at Aberdeen Proving Ground (APG), MD.

We were able to obtain facet descriptions of the target vehicles from the Virtual Targets Center (VTC), Army Model Exchange, https://modelexchange.army.mil, consisting of about 800,000 flat, triangular facets as shown in Figure 1. Simulation of this size target using Xpatch requires about 20 CPU min for 256 frequencies at each incident angle when using the recommended 10 rays/wavelength in the shooting and bouncing ray (SBR) method. This represents a typical time for far-field calculations and the actual time required varies with azimuth and depression angle (due to different multi-bounce calculations). In order to compute the SAR image at 256 frequencies for a full 360° azimuth sweep in 0.015° steps would require 8000 CPU hr. Since Xpatch defines the target surfaces by the ray hit points and then the ray density determines the resolution at which the target is "sampled", hence the typical 10 samples/wavelength. Using 10 rays/wavelength at K_a-Band amounts to sampling the target at a higher resolution than at X-Band. But we are using the same facet files at all frequencies and a denser grid of rays does not provide any additional target information. So we use the same X-Band ray density (i.e., the same rays/unit area) at K_a-Band corresponding to 3 rays/wavelength. We have shown that this approach provides sufficient accuracy at K_a-band with a factor of 5 savings in CPU time[4,5]. Of course if we had higher resolution facet descriptions then the ray density would be adjusted accordingly.

This still amounts to 67 days on a single CPU, but each simulation angle run is totally independent from the simulation of other angles so we can take advantage of the HPC multiprocessors and scripting languages to reduce the total clock time using many processors running simultaneously. It is now feasible to generate the synthetic far-field data needed to form a complete set of

Synthetic Aperture Radar (SAR) images for a full 360° sweep in a reasonable amount of time. To create a complete set of free-space results for one depression angle takes about a day turnaround time (with typical usage of HPC resources) since we can utilize several hundred concurrent processors.

Including the properties of the radar in the Xpatch near-field scattering simulation can be important for comparison to measured data but introduces about a factor of 11 additional CPU time. Either a non-metallic vehicle or a dielectric ground plane would introduce a similar computational penalty. We investigate the problem that the predicted RCS in free-space is often too large at K_a-band by conducting a parameter study to demonstrate the cause of the major discrepancies. In this paper we will present some of the simulation and model fidelity issues that can lead to discrepancies when comparing synthetic data to measured radar signatures.

2. Problem and Methodology

Two tracked vehicles with available RCS data are the ZSU-23-4, a quad 23-mm self-propelled anti-aircraft weapon system and the T72M1 main battle tank. ARL measured the target signatures at the Radar Signature Research Facility of the US Army Aberdeen Test Center located at Air Base Range 8 of APG, MD[6,7]. Additional measurements on the ZSU-23-4 were obtained in 2001. At X-band a ground plane in the Xpatch simulations was included to represent the foreground in the vicinity of the turntable and this provided better agreement with measurements[8]. Comparisons at K_a-band using the same target facet models were not as favorable and are the subject of this paper.

The virtual models include material descriptions but we define transparent materials (e.g., glass, rubber weather seals, etc.) as perfectly absorbing to avoid artificial cavities since no attempt is made to model the interior surfaces. In this way we avoid exposing the missing or crude representation of surfaces behind these materials. Otherwise we obtain spurious returns from transparent materials represented as metal or from unrealistic openings and cavities. Examples are the rubberized weather seals on the T72M1 main gun and launch tubes. Other non-metallic features such as rubber skirts and tires are typically removed and often corresponds to an upper bound on the target signature. The T72M1 is an example where this approach exposes the wheel surfaces and allows a multi-bounce path with the hull producing a significant return. If we retain the rubber materials we obtain results more consistent with measurements since we disrupt the phase of these multi-bounce contributions. We can accomplish a similar effect by making these surfaces perfectly absorbing which saves a factor of seven in CPU time compared to real materials.

Tracked Vehicle Simulations. With near-field RCS calculations, better agreement to measurements can often be obtained at K_a-Band and above. The antenna pattern and range to the radar used at the ARL Signature Research Facility were incorporated into the Xpatch scattering simulation in order to improve the fidelity of the synthetic signatures compared to these measurements. The K_a-Band radar antenna beamwidth is sufficiently narrow to only illuminate the target so a ground plane model is not required. Information about the actual test vehicle is critical to confirm the simulation fidelity and reproduce the target configuration and orientation of articulated parts. More of these details are available for the ZSU-23-4 measurements, allowing better simulation fidelity compared to the T72M1 data for which only limited information is available.

The remaining discrepancies are primarily associated with model fidelity in the representation of the test vehicle. The largest error appears to be an overestimate of the signature at some view angles associated with artificial multi-bounce returns involving the vehicle tracks, wheels, and hull. The track assemblies are typically generated in the model by replication of a single cleat and wheel part and are an idealized representation of fielded vehicles as can be seen in Figure 2.

This is a typical problem with replicated surfaces and the effect on the synthetic signature becomes more obvious at K_a-Band and above. In all cases we represent the track assembly with perfect absorber surfaces to eliminate this issue without changing the shadowed portions of the target. Introducing a random variation in the orientation and/or position of replicated parts could reduce these spurious multi-bounce contributions. When we remove the rubber skirts and tires on the T72M1 model we expose the pristine wheel/hull surfaces leading to large multi-bounce returns at low depression angles. The effect on the RCS is shown in Figure 3 for the cross-polarized return.

This does not address the pristine nature of other parts of the virtual target such as perfectly orthogonal corners, but the wheel/hull area is a source of large discrepancies in the calculated RCS. We effectively eliminated these spurious returns for the ZSU-23-4 by making the tracks perfect absorber. For the T72M1 we had to retain the rubber skirts and tires in the facet model to avoid spurious multi-bounce returns from metal surfaces not normally exposed. Alternatively we can make these surfaces perfectly absorbing, which allows a factor of seven faster run-times, but the RCS then represents a lower bound to the target signature. These types of discrepancies due to model fidelity may be improved by obtaining more realistic target representations. Our approach is a compromise between accuracy and speed and we attempt to use consistent models based on this type of physical reasoning. We summarize our comparison results after modification of the targets based on a detailed parametric study of the largest discrepancies observed for these two tracked vehicles.

Canonical Tank Simulations. We also use a variant of the T5M3 scale-model target shown in Figure 4 to investigate model fidelity issues for a simple target. The presence of a realistic ground plane may be important for simulation of combat vehicles, but this depends on the applications for the synthetic signatures. In our case the measured data corresponds to far-field RCS under free-space conditions so the Xpatch simulations are significantly faster compared to real vehicles. The target includes small corner features as can be seen by the specular flash in the photograph. These returns were not so obvious at K_a-Band but become one of the dominant features in the W-Band synthetic signature. Otherwise the synthetic and measured RCS are in good agreement for this simple target and the Xpatch results would be sufficient for many applications. We compare the Xpatch results to the measured RCS from the NGIC compact range[9,10].

3. Results

We have previously shown that it can be important to include the ground plane shape and electrical properties into the vehicle model. This improved the agreement between the X-band synthetic results and measurements for all polarization channels[8]. When the radar antenna pattern has sufficiently narrow beamwidth that only the target is illuminated then a ground plane model is not required. However, the radar slant range is on the same order as the near-field to far-field transition region and scattering calculations at fixed range are more appropriate. A good approximation to the radar antenna pattern[11] is used in the Xpatch near-field scattering simulations to better reproduce the measured data. This approach often reduces the cardinal peaks and sometimes multi-bounce returns but can also result in features not obtained in the far-field signature. An example of the difference in SAR image is shown in Figure 5 for the T72M1, where a distinctive scattering center in the measurement was not obtained in the far-field simulation. Even with perfect absorber tracks the wheels can be seen in the image as distinct scattering centers as indicated in Figure 5(b). This effect is reduced in the near-field results where the wheels are apparent but less distinctive. The near-field calculation provides better agreement than the far-field RCS when compared to near-field measurements but in our cases the difference at K_a-Band is not always significant.

The predicted RCS for vehicle targets is often larger than measured in the intercardinal regions where multi-bounce returns tend to dominate the signature. Realistic targets can include surface waviness and random or systematic errors in the fabrication and assembly of the exterior surfaces. To avoid this issue we make some of these unrealistic surfaces perfectly absorbing which retains the correct shadow boundaries but eliminates their contribution to the RCS. For the ZSU-23-4 these surfaces include the tracks and four flat facets representing the engine block which are made perfectly absorbing. The VV- and HV-channel near-field RCS comparisons for the modified ZSU-23-4 in free space are shown in Figure 6 at depression angles of 10° and 15°. Our experience with facet models has been that the track assembly is too artificial compared to real vehicles and these idealized metal surfaces lead to spurious returns. These parts cannot be removed without changing the signature so we eliminate their contribution by making the track assembly perfectly absorbing. This approach is used consistently throughout this study and so the results represent a lower bound to the target signature. Although this method cannot be completely justified we prefer to obtain a realistic bound to the target signature rather than significantly overestimating the RCS.

Irregular surfaces result from realistic fabrication tolerances and practices even on new vehicles, but the facet models do not include such small variations in the position and orientation of surfaces, and so represents a "pristine" version of the test vehicle. Other researchers have reached similar conclusions with the implications that virtual models should represent test targets to dimensional accuracies on the order of a wavelength[12]. The Xpatch results tend to overpredict the K_a-band RCS compared to real targets and this effect can often be more apparent in the SAR image as overly bright or spurious scattering centers. This is especially true for tracked vehicles so in all cases we eliminate the contribution of these multi-bounce returns by making the tracks perfectly absorbing. Once this is done, the multi-bounce returns for the T72M1 are dominated by interactions with the metal wheels and hull. The contribution of these metal surfaces is much different when including rubber (ε_r = 4) skirts, tires and mud guards. Alternatively we can make these parts perfectly absorbing with similar results but obtain roughly a factor of seven faster run times.

The VV- and HV-channel near-field RCS comparisons for the different modifications of the T72M1 in free space are shown in Figure 7 at 10° and 15° depression angles. There is little difference between the perfect absorber or rubber parts and both significantly change the cross-polarized RCS compared to removing these parts (see Figure 3). The largest discrepancies remaining are associated with the pristine nature of ammunition boxes mounted on the rear of the turret. The discrepancies are most obvious in the HV-channel across the rear of the target where Xpatch overestimates the measured RCS.

The canonical tank target is an example of how model fidelity is related to frequency even for such a simple target. The square corners have dimension b = 2.16-in and exhibit the expected response at X- and K_a-Band. Near the corner bisector the maximum return would be $\sigma_{max} \sim 12\pi b^4/\lambda^2$ or 6.4 dBsm at K_a-Band[13]. Xpatch obtains the expected result ~ 15 dBsm at W-Band where this maximum would be reduced at least 3 dB for a deviation error on each face of only 2 mil[13]. The W-Band data indicates that these features no longer appear as right angle corners and the broad peaks are much smaller than calculated.

The comparison for the T5M3 VV-channel RCS is shown in Figure 8 at a 30° depression angle. Good agreement is obtained at K_a-Band except for certain view angles where multi-bounce returns involving curved surfaces are a significant contribution to the RCS. At W-Band these discrepancies are more apparent as might be expected but now the return from the cut-outs is over predicted which was not obvious at K_a-Band. The size of the cut-outs in the scale model target would require fabrication accuracy to better than 2 mil to obtain an orthogonal corner relative to a wavelength. It has been recognized that a sufficiently accurate representation of the "as-tested" vehicle should produce better results, and laser scanning systems with much better resolution than current systems are under development[14]. Of course significantly increasing the number of facets will increase the CPU time so as usual there will be a tradeoff between accuracy and computational efficiency.

4. Significance to DoD

Programs to design and develop the next generation of the Nation's combat systems rely heavily on modeling and simulation to provide guidance on the integration of competing and, in some cases, conflicting requirements for performance and survivability, and to reduce the development and life-cycle costs through smart design. For Army combat and support systems, the nonballistic survivability suite of requirements now includes RCS specifications and guidelines. The active development of FCS vehicle variants are specific examples, but this is only one representation of an inevitable trend. To develop, investigate and quantify various RCS performance options, ARL is applying the Department of Defense (DoD) software, Xpatch. Army requirements for FCS extend into the MMW range of the EM spectrum where model and simulation fidelity limitations often determine the quality of signature predictions compared to measurements.

Another area of potential DoD use for our results is the direct application of simulation and modeling to modify/improve/enhance existing RCS measurement capability. We have gained experience with the near-field modeling capability in the latest release of Xpatch and its use provides better agreement to the available data. Recognizing this difference between near-field data and far-field predictions has been an important aspect of our validation studies when using signature data for large targets such as vehicles. We believe that the near-field RCS results will prove of great utility in modeling the radar data collection facility, in providing feedback on techniques that would increase the accuracy of radar measurement data, and in optimizing the radar system itself. Unfortunately, this simulation option can introduce a factor of three additional CPU time for each polarization channel significantly increasing the computational requirements.

We have examined the performance of Xpatch at K_a-band compared with measured data on ground vehicles and have gained insight on issues related to the quality and fidelity of simulation results that will have direct application to future Army systems. We often quantify the comparison results in terms of the difference in mean and median RCS. Our modified target models improve the agreement by over 3 dB compared to all metal facet models (except cavity openings which we always seal with perfect absorber). The comparison metrics for our modified targets are summarized in Table 1 for the VV-channel RCS where negative values indicate that the synthetic results are larger than measured. In most cases these differences are within the measurement error of 1 dB and similar agreement is obtained for the other RCS-channels.

Table 1. K_a-Band near-field RCS comparison VV-channel summary in terms of the difference in mean and median values over all azimuthal angles at K_a-Band

Target Vehicle	Depression Angle (degrees)	VV-channel Difference (dB) Mean	VV-channel Difference (dB) Median
ZSU-23-4	5	1.0	0.8
ZSU-23-4	10	-1.1	-0.6
ZSU-23-4	15	-0.2	-0.5
ZSU-23-4	30	0.7	0.3
T72M1	1	1.1	-0.5
T72M1	5	-0.4	-0.2
T72M1	10	-0.8	-0.7
T72M1	15	-0.8	-0.9

We have also investigated the use of Xpatch for canonical tank shapes having only a few complicating features. For such simple targets good agreement can be obtained at K_a-Band but at some frequency the virtual target still appears pristine compared to the actual scale-model target. We have used such notional targets to demonstrate capabilities and provide clear examples for the modeling issues expected at even higher frequencies.

5. Systems Used

We use the ARL MSRC Grid Engine (GE) queuing system to transfer jobs to available processors. The ARL MSRC has implemented user-transparent support for jobs on all the various HPC platforms, thus greatly expanding the actual number of processors available to a user at any given time. The GE supports the concept of a single batch job that consists of multiple tasks as a batch job array. The user is able to submit a single job array to transfer a large number of jobs to be run concurrently on multiple platforms as processors become available. In this way we are able to take advantage of idle processors across many HPC platforms. Without this capability the simulations at frequencies above X-band would not be practical for the complex targets of interest.

Typical computational requirements for ground vehicles are summarized in Table 2 for the different types of Xpatch simulations at 256 K_a-Band frequencies. We assume 100 CPUs are used concurrently for the SAR image calculations at 24000 azimuthal angles. If more processors are available, or SAR images are not required (i.e., less angular resolution), than the turn-around times would be corresponding reduced. With only 100 processors this study of tracked vehicles would amount to 7 CPU months. A similar study at W-Band would require 32 CPU months and correspond to over 2 million CPU hours. Obviously more than 100 processors are required and the availability of substantial HPC resources is critical for MMW signature predictions of ground vehicles.

Table 2. Summary of typical computational requirements for Xpatch simulations of vehicles at K_a-Band

Xpatch Simulation Type (Using 256 Frequencies)	Typical CPU Time (min/angle)	Penalty Factor	Total Time with 100 CPUs (hrs)
Free-Space Far-Field	4	1	16
Perfect Ground	25	6	100
Dielectric Ground	42	10	168
Free-Space Near-Field	45	11	180

We use workstations and PCs for post processing and scientific visualization. For scientific visualization we often use the tools available within Xpatch such as ray trace back to determine scattering centers. Visualization capability has proven to be an important aspect of our radar signature modeling studies and validation efforts.

6. CTA

This project is associated with the Computational Electromagnetics and Acoustics (CEA) CTA. The targets of interest at high frequencies represent some of the most challenging problems in the computational electromagnetics community.

References

1. Andersh, D.J., et al., "Xpatch: A High Frequency Electromagnetic Scattering Prediction Code and Environment for Three-Dimensional Objects." *IEEE Transactions on Antennas and Propagation*, vol. 36, February 1994, pp. 65–69.

2. Song, J.M., et al., "The Fast Illinois Solver Code." *IEEE Antennas and Propagation Magazine*, vol. 40, No. 3, June 1998.

3. Carter, S.L., *T5M3 Trihedron RCS Anomalies*; NGIC-1141-0331-00, National Ground Intelligence Center.

4. Le, C.D. and W.O. Coburn, "High Performance Computing Numerical Study of a Ground Vehicle Radar Cross Section." *Proceedings of the 12th Annual Ground Target Modeling and Validation Conference*, August 200, pp. 115–121.

5. Coburn, W., C. Kenyon, C. Le, A. Sullivan, and R. Namburu, "Radar Signature Modeling for Combat Systems." *IEEE Computer Society Proceedings of the 2003 Users Group Conference*, 2003, pp. 68–73.

6. Stratton, S.R., H.B. Wallace, and R. L. Bender, "Radar Cross-Section Measurements of the ZSU-23-4 at X- K_a- and W-Bands." *ARL-TR-1722*, US Army Research Laboratory, Aberdeen Proving Ground, MD, August 1998.

7. Stratton, S.R., H.B. Wallace, R.L. Bender, and A.E. Brodeen, "A Comparison of the Radar Cross-Section (RCS) Measurements of 11 T72M1 Tanks at 35 GHz." *ARL-TR-1421*, US Army Research Laboratory, July 1997.

8. Coburn, W.O. and C.D. Le, "An Investigation of the ZSU-23-4 Radar Cross Section at X-band." *ARL-TR-3003;* US Army Research Laboratory, June 2003.

9. Spurgeon, W.A. and D.A. Hopkins, "An Xpatch Study of the T5M3 Simulator and Three Simpler Variants." *ARL-TR-2851*, US Army Research Laboratory, Aberdeen Proving Ground, MD, September 2002.

10. Spurgeon, W.A., "RCS Modeling and Validation of a Second Revised T5M3 Ground Vehicle Simulator and the Effects of a Ground Plane on RCS," US Army Research Laboratory, Aberdeen Proving Ground, MD, (in press).

11. Bender, R. Personal communication with W. Coburn. US Army Research Laboratory, Adelphi, MD, 14 January 2003.

12. Vechinski, S.R. and S.D. McKenzie, "BTR-80 W-Band Signature Simulation." Science Applications International Corp. technical report, December 31, 2000.

13. Crispin, J.W. and K.M. Siegel, ed., *Methods of Radar Cross-Section Analysis*, Academic Press, New York, 1968.

14. Cook, J. Personal communication with W. Coburn. Science Applications International Corp., Huntsville, AL, 3 April 2003.

Figure 1. Facet models for the (a) ZSU-23-4 and the (b) T72M1 vehicle targets

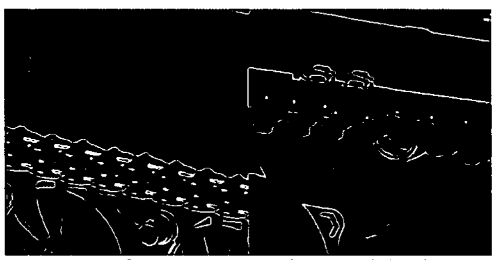


Figure 2. View of the hull area for the (a) ZSU-23-4 and (b) T72M1 vehicle models

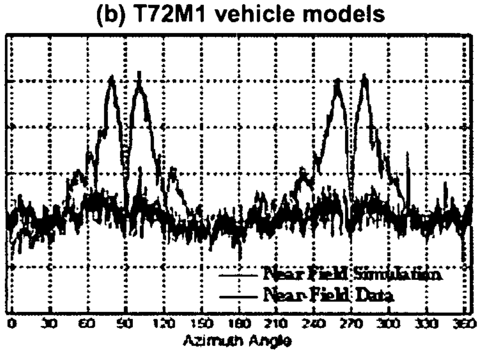


Figure 3. K_a-Band cross-polarized RCS at a 15° depression angle for the T72M1 having perfect absorber tracks but rubber skirts, tires and mud guards removed

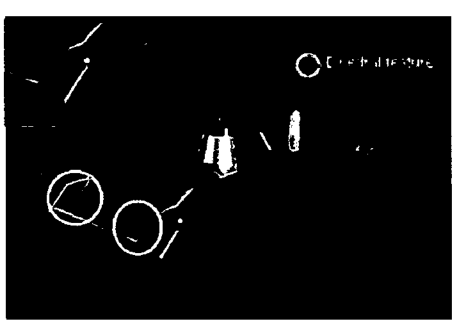


Figure 4. T5M3 (Mark1) 1/16-scale model target (approximate dimensions 15-in L x 8-in W x 5.375-in H) having 0.135-in square cut-outs at each corner

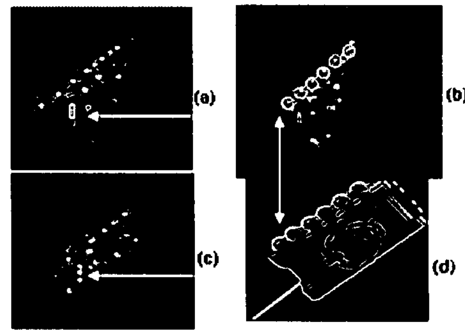


Figure 5. K_a-Band SAR image comparison for the T72M1 at 15° depression and 30° azimuthal view angle (a) Xpatch near-field RCS, (b) Xpatch far-field RCS, (c) near-field measurement, (d) target model

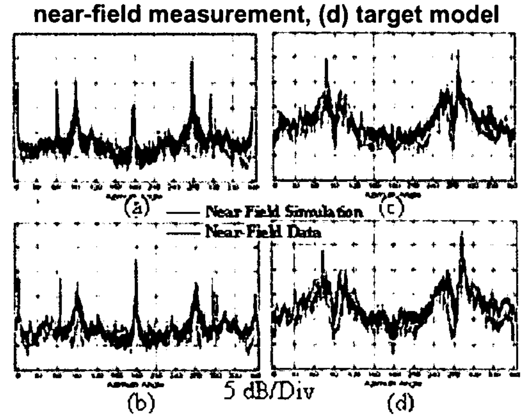


Figure 6. K_a-Band near-field RCS comparison for the modified ZSU-23-4; VV-channel at (a) 10° and (b) 15° depression angle and for the HV-channel at (c) 10° and (d) 15° depression angle.

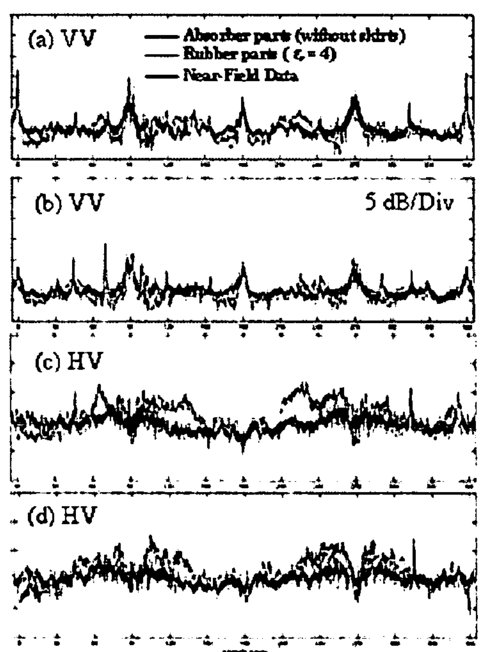
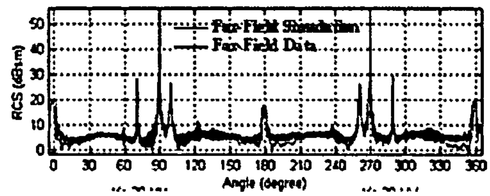
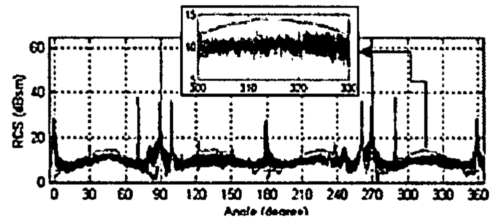


Figure 7. K_a-Band near-field RCS comparison for the modified T72M1; VV-channel at (a) 10° and (b) 15° depression angles; HV-channel at (c) 10° and (d) 15° depression angles.



(a)



(b)

Figure 8. T5M3 (Mark1) far-field RCS comparison of the VV-channel at a 30° depression angle in (c) K_a-Band and (d) *W*-Band